Potential for Conservation Practices to Reduce Greenhouse Gas Emissions on Croplands - Maine

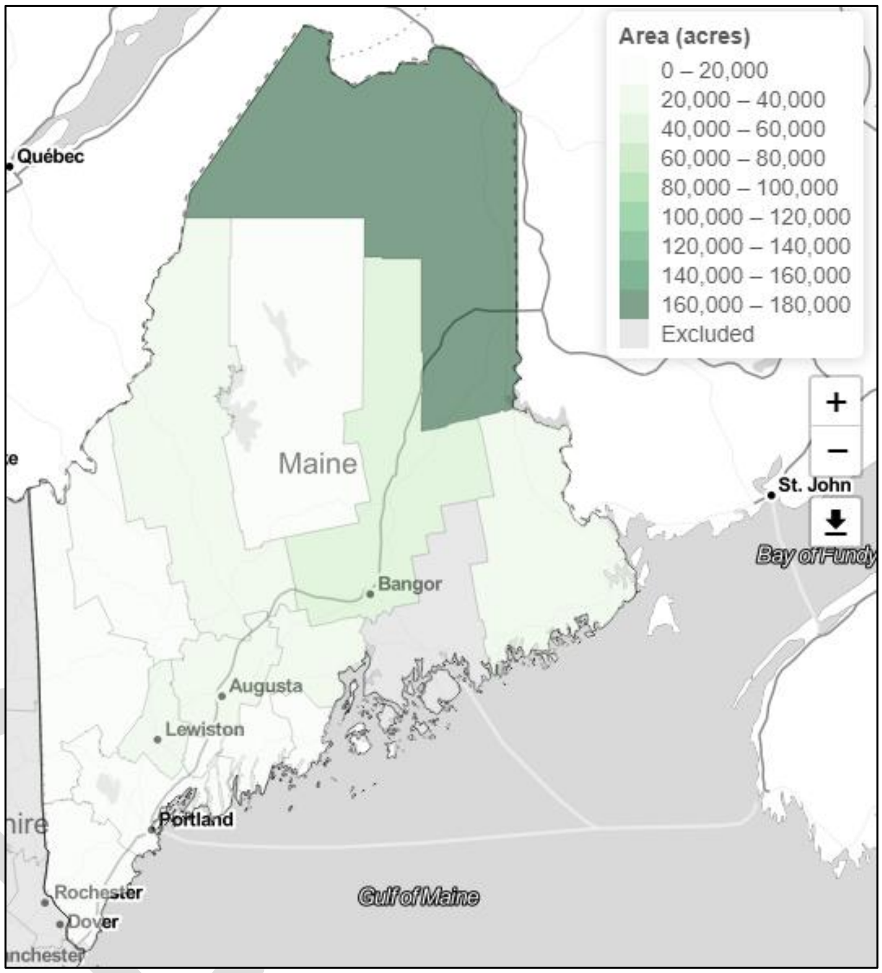

Image: Cropland acres for each county across Maine as created using the Carbon Reduction Potential Evaluation Tool (CaRPE Tool™) using 2017 AgCensus data.

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Draft report last update: 4 February 2020

Table of Contents

List of Figures

List of Tables

Executive Summary

Implementation of agricultural conservation practices on croplands has the potential to provide short-term as well as long-term GHG mitigation opportunities through reductions in GHG emissions and sequestration of carbon in soils. How these practices differ in their mitigation potential and how these scale over the landscape are not easily estimated at the state and county level. The overarching goal of this report is to estimate county-level GHG mitigation potential of various *NRCS cropland conservation practices* based on current adoption levels and scenarios of additional practice adoption. All cropland values and climate benefits in this report are estimated values and should be used for general planning purposes only.

In order to evaluate the current and projected GHG mitigation potential we developed the interactive Carbon Reduction Potential Evaluation (CaRPE) Tool to quantify and visualize county-level GHG emission reductions resulting from the implementation of a suite of cropland and grazing land management practices. The CaRPE Tool™ scales the emission reduction coefficients (ERC) extracted from the COMET-Planner tool to the county level by coupling the coefficients with cropland acres from the 2017 Census of Agriculture (AgCensus). This report focuses exclusively on cropland practices with an emphasis on tillage and cover crop adoption given those adoption rates are specifically provided in the 2017 AgCensus data.

The total amount of farmland in Maine is 1,307,613 acres with 472,508 of those acres under cropland. Current adoption of cover crops (12%) and conservation tillage (35%) in Maine is estimated to reduce agricultural GHG emissions by up to 27,589 tonnes CO_2e yr^{-1}. If all of the remaining cropland had a legume cover crop planted and the land currently in conventional till or reduced till went to no-till, the state could reduce GHG emissions by an additional 153,000 tonnes CO_2e yr^{-1} for a total (current and remaining) potential of up to 181,000 tonnes CO_2e yr^{-1} for just these two USDA-NRCS supported conservation practices. Recognizing that 100% adoption of any one practice is not likely, one scenario was developed to represent a 25% increase in cover crop adoption, a 75% increase in reduced or no-till adoption, and a 25% increase in adoption of nutrient management strategies that replace 25 % of synthetic nitrogen inputs. Under this adoption scenario (i.e., cover cropping, tillage management, and nutrient management), Maine could reduce greenhouse gas emissions by approximately 66 to 143 thousand tonnes CO_2e yr^{-1}.

The intent of this report is to provide county-level GHG emission estimates for cropland that states can use to evaluate potential GHG reductions, assess the impact of existing and new programs, and inform current and future conservation programs to provide greater GHG offset benefits. Maine cropland management has significant potential to reduce GHG emissions and sequester carbon. Using current and future adoption scenarios, coupled with COMET-Planner emission reduction coefficients, the GHG reduction potential from agricultural best management practice adoption can be estimated using the CaRPE Tool™. This provides an assessment tool of the win-win opportunities to improve long-term agricultural productivity while also mitigating GHG emissions.

1 Introduction

1.1 United States Climate Alliance – Natural and Working Lands Challenge

The U.S. Climate Alliance (USCA) is a bipartisan coalition of 25 governors committed to reducing greenhouse gas (GHG) emissions consistent with the goals of the Paris Agreement. The USCA represents 55% of the U.S. population and 60% of national Gross Domestic Product. The USCA states are committed to reducing GHG emissions by 26 to 28% below 2005 levels by 2025 thereby advancing the goals of the Paris Agreement. Among the numerous USCA initiatives, the Natural and Working Lands Initiative identifies best practices for land conservation, management, and restoration to increase carbon storage (i.e., carbon sequestration). Enhancing carbon sequestration on natural and working lands has been identified as a key near-term opportunity for achieving state climate goals. Specifically, an emphasis has been placed on the role of forests, farmlands, ranchlands, grasslands, wetlands, and urban lands to mitigate the harmful effects of climate change.

1.2 Climate Change Threats to Agriculture

Extreme weather events, including record high temperatures, drought, and flooding, threaten U.S. crop productivity. The World Meteorological Organization (2019) reported that twenty of the hottest years on record have occurred in the last twenty-two years. Increased temperatures are predicted to impact crop germination, harvest timing, and crop yield. Whereas some crops might benefit from a longer growing season, the species and varieties of crops grown in an area are projected to shift, resulting in the need for new equipment, knowledge, and resources to maintain agricultural viability (Roesch-McNally et al., 2019). Other impacts include greater risks of disease, insect, and weed pressures due to higher temperatures, longer growing seasons, and greater frost-free days. This is anticipated to increase dependence on inputs such as fungicides, herbicides, and insecticides.

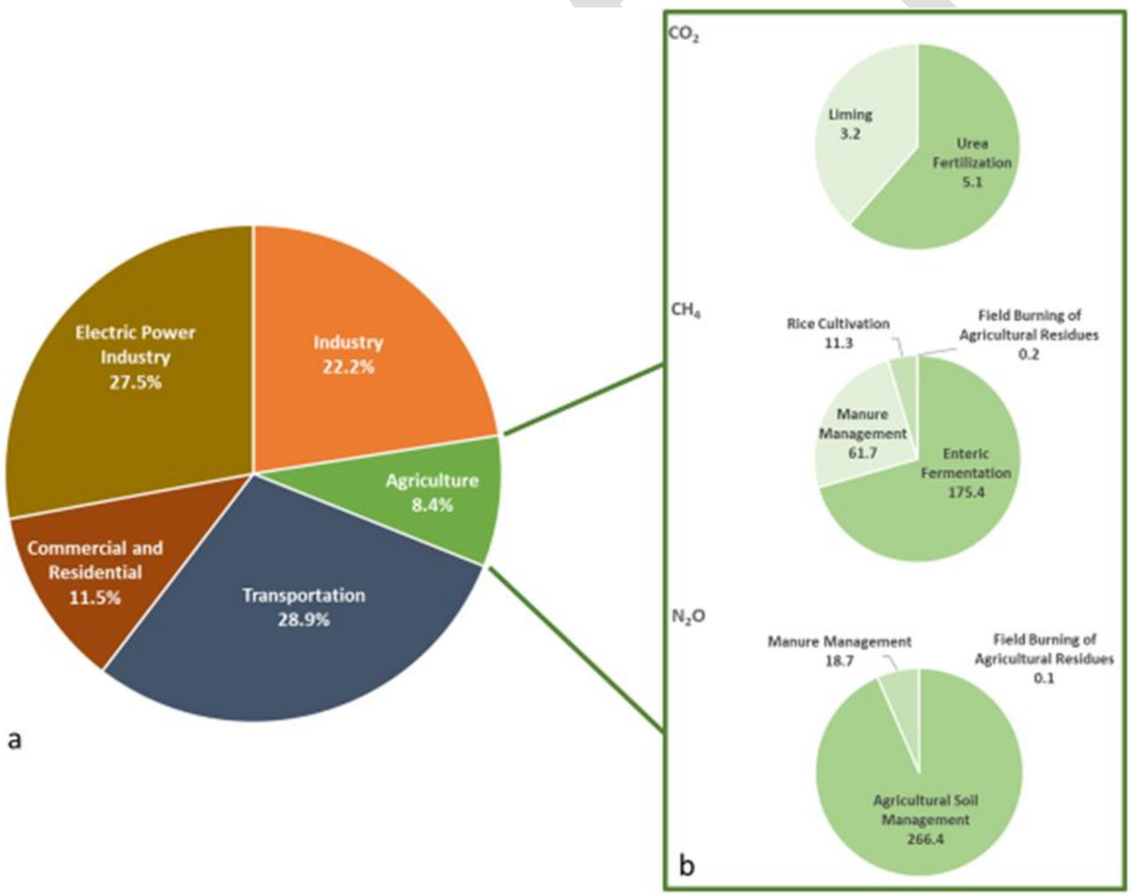
In addition to higher temperatures, some areas will experience increased duration, frequency, and intensity of drought while other areas will be subjected to more intense storms contributing to increased incidences of major flooding. Higher temperatures and increased drought increase stress on both livestock and crops, thus requiring greater inputs to maintain plant and animal health. It has been observed that so-called 500-year floods have become 100-year floods making planting and harvest more difficult. For example, in 2019 the Midwest experienced unusually wet conditions leading to one of the latest planting seasons on record (Rippey, 2019). Furthermore, major flooding imperils infrastructures such as roads, railroads, barge landings, and buildings necessary for agricultural product storage and processing. Other concerns, especially in western states, involve the reduction in snowpack amount and earlier peak flows (snow melt), which would reduce water availability during the growing season (Roesch-McNally et al., 2019).

Collectively, these extreme weather events negatively impact the nations soil and water resources, stress water supplies, and increase wildfire risks. Increased extreme weather events could compound soil health and water quality concerns through increased soil loss from erosion and flooding. Heavy and earlier spring rains or flood events will delay planting or force farmers to perform field operations (e.g., tillage, planting) when the soil is susceptible to compaction or erosion. Drought and high temperatures will result in increased wildfire risk which threatens homes, fields, livestock, wildlife, and, human life. Furthermore, smoke damage for certain susceptible specialty crops (e.g., wine grapes) has resulted in decreased quality and can negatively affect farmers and farm workers exposed to unhealthy air conditions. Overall, extreme weather events observed and predicted under future climate change present a multitude of challenges to national food security and the US economy.

1.3 U.S. Agriculture's Contribution to Greenhouse Gas Emissions

Gross U.S. GHG emissions were 6,456.7 million metric tons (MMT) CO_2e in 2017 (EPA, 2019). Agriculture accounted for 8.4% of the total 2017 US GHG emissions (Figure 1). In 2017, US emissions were 1.3% higher than 1990 levels but 0.5% below 2016 emission levels. The primary greenhouse gases emitted by the agricultural sector were carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) (Figure 1). The major source categories within agriculture include agricultural soil management, enteric fermentation manure management, rice cultivation, urea fertilizer application, liming, and field burning (EA, 2019). Agricultural N_2O emissions, from soil management activities, are the largest source of total 2017 US N_2O emissions.

Figure 1. 2017 US Greenhouse Gas Emissions a) by economic sector as % of total US emissions (6,456.7 MMT CO_2e) and b) within the agricultural sector as million metric tons of carbon dioxide equivalents (MMT CO_2e).



Note: Adapted from EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017 (EPA, 2019).

1.4 Agriculture's Contribution to Climate Change Mitigation

Although agriculture currently is a net source of GHG emissions, farmers and ranchers are poised to be one of our nation's greatest allies in fighting climate change. Soils store 2 to 3 times more CO_2 than the atmosphere and 2 to 5 times more carbon than that stored in vegetation (IPCC, 2013). Numerous cropland and grazing land management practices have been shown to increase the amount of carbon plants can capture and ultimately store belowground in the soil. This process is called soil carbon sequestration. Lal (2004) estimated that 50 to 66% of historic carbon losses on agricultural and degraded soil might be restored by adopting practices that sequester soil carbon, thereby partially mitigating rising atmospheric CO_2 concentrations (West and Post, 2002). Agricultural practices shown to partially restore depleted soil organic carbon include: (1) adoption of conservation tillage including no-tillage; (2) intensification of cropping by eliminating fallow, cover cropping, and integrating perennial crops in rotation; and (3) improving biomass production through the use of soil amendments (e.g., composts and manures), fertilizers, and high yielding crop varieties (Lal et al., 1998; Follett, 2001; Paustian et al., 2001; Post et al., 2001; West and Post, 2002; Sperow et al., 2003).

With more than 900 million acres of agricultural land in the US, the opportunity to rebuild soil organic carbon, sequester atmospheric carbon, and reduce N_2O and CH_4 emissions are considerable. Some estimates suggest that if we were able to adequately address economic, social, and technical barriers to implementing best soil management practices, US croplands have the potential to sequester 1.5 billion to 5 billion metric tons of CO_2e per year for 20 years (Sanderman et al., 2017; Zomer et al., 2017). Moreover, the same agronomic practices that increase carbon sequestration also help to mitigate flood events, protect water quality, recharge groundwater, and increase resilience to drought (Lehman et. al, 2015).

1.5 Report Goal

Implementation of agricultural conservation practices on croplands has the potential to provide short-term as well as long-term GHG mitigation opportunities through reductions in GHG emissions and sequestration of carbon in soils. How these practices differ in their mitigation potential and how these scale over the landscape are not easily estimated at the state and county level. The overarching goal of this report is to estimate county-level GHG mitigation potential of various *NRCS cropland conservation practices* based on (i) current adoption levels; and, (ii) scenarios of additional practice adoption. All cropland values and climate benefits in this report are estimated values and should be used for general planning purposes only.

Note: We recognize that the agricultural sector includes other critical land management sectors (e.g., grazing lands, riparian, and coastal habitats) and associated best management practices that are not considered in this assessment. Future efforts will seek to include those for a more holistic portfolio of state and county specific options to optimize the climate benefits from agricultural best management practices, conservation programs, and policies.

2 Approach

In order to evaluate the current and projected GHG mitigation potential across the entire USA, we developed the interactive Carbon Reduction Potential Evaluation (CaRPE) Tool that couples cropland and grazing land data from the Ag Census (USDA-NASS, 2017) with GHG emission reduction coefficients reported in COMET-Planner for each county in the US. The COMET-Planner tool provides general estimates of GHG emission changes resulting from the implementation of various conservation practices, many of which are supported by USDA-NRCS Farm Bill programs (Swan et al., 2019). For the purpose of this report, we focus exclusively on the cropland management practices identified in COMET-Planner. The full mitigation potential of each practice is the combined effect of GHG emission reduction and soil C sequestration changes. Assessments using COMET-Planner are designed to be appropriate for multi-county to regional planning purposes based on the combined spatial and temporal metamodeling approach of COMET-Farm.

Our intention is to provide county-level GHG emission estimates for cropland that states can use to: i) evaluate potential GHG reductions; ii) assess the impact of existing and new programs; and, iii) inform current and future conservation programs to provide greater GHG offset benefits, as appropriate. The use of 'potential' in both current and projected estimates was intentional to highlight that reported values are generalized estimates. It is important to keep in mind that not all conservation practices may be suitable or practical to all land use types. County- or region-based agricultural experts (e.g., university extension, soil and water conservation districts, NRCS, ag consultants, etc.) should be consulted to target the adoption of practices to cropping systems and ensure that implementation meets NRCS practice standards. We encourage states to reach out to our team to develop additional estimates for other agricultural and field border management options.

2.1 Background on CaRPE Tool™:

The CaRPE Tool™ was designed to quantify and visualize county-level GHG emission reductions resulting from the implementation of a suite of cropland and grazing land management practices. For the purpose of this report, we focus exclusively on cropland practices with an emphasis on tillage and cover crop adoption. Tillage and cover cropping were emphasized in current reports because adoption rates are specifically provided in the 2017 Ag Census data (NASS, 2017). The CaRPE Tool™ scales the emission reduction coefficients (ERC) extracted from the COMET-Planner tool to the county level by coupling COMET-Planner GHG reduction coefficients with cropland acres from the 2017 Census of Agriculture (AgCensus). Irrigated and non-irrigated cropland acres were calculated for each county using the total cropland, harvested cropland, harvested irrigated cropland, and total irrigated acreage data from the Ag Census. For each of the cropland management practices in COMET-Planner, the appropriate irrigated or non-irrigated cropland acreage was multiplied the appropriate ERC to generate total annual CO_2e reduction estimates (tons of CO_2e yr^{-1}).

There are eight general cropland management categories available in COMET-Planner that are aligned with USDA-NRCS Conservation Practice Standards (CPS):

1. Conservation Crop Rotation (CPS 328);
2. Mulching (CPS 484);
3. Stripcropping (CPS 585);
4. Cover Crops (CPS 340);
5. Residue and Tillage Management (CPS 329 and CPS 345);
6. Nutrient Management (CPS 590);
7. Combined Practices (11 combinations of CPS 329, CPS 340, and CPS 590); and
8. Combustion System Improvement (CPS 372).

For summary definitions of each of the above management categories, please refer to the *Appendix.*

Results in this report are organized into three broad groups:

1. *Current Adoption of Cover Cropping & Conservation Tillage*
2. *Current & Future Potential GHG Benefits with Cover Crop and Conservation TillageAdditional Cropping System GHG Reduction Potential Opportunities for Cropland*

2.2 Visualization & Quantification of Current Adoption: Cover Crop & Conservation Tillage

For visualization and quantification of current adoption of cover cropping and conservation tillage, we used the county-level values as reported in the 2017 AgCensus. Current adoption is reported both as a percent of total cropland acres and as total acres of practice adoption. For the 2017 AgCensus, participants were instructed to report acres planted to cover crop with cover crops defined as a crop "planted primarily to manage soil erosion, soil fertility, soil quality, water, weeds, pests, and diseases" on non-CRP acres (NASS, 2017). For tillage, survey participants were instructed to report acres of land under 1) no-tillage; 2) reduced tillage; and 3) intensive tillage practices (NASS, 2017).

No-till was defined as cropland used for production from year to year without disturbing the soil through tillage other than planting. Ag Census survey participants were instructed to not include as no-till, land that was not planted in 2017 such as existing orchards, land in berries, nursey stock, or hay harvested from existing grassland or alfalfa that was established prior to 2017. Reduced tillage was defined as management practices that leaves at least 30% residue cover on the soil. This may involve the use of a chisel plow, field cultivators, or other implements. Intensive tillage inverts or mixes 100% of the soil surface leaving less than 15% of crop residue of small grain residue. Intensive tillage often involves multiple operations with implements such as a mold board, disk, and/or chisel plow.

Defining Cropland Acreage using the 2017 Census of Agriculture

Total cropland acreage for this analysis was determined by subtracting the government program land acreage from the total cropland acreage as reported in the 2017 Census of Agriculture. This decision was based on the survey instructions in which survey respondents were instructed to report CRP, WRP, FWP, and CREP[1] acres in the most appropriate land use category. Since there is no way to ascertain where these government program acres were assigned by survey respondents, removing them from the total cropland acreage was considered to provide a more conservative climate benefit estimate. For this analysis, hayland acreage reported by the 2017 Census of Agriculture was not removed from the total cropland acres used to assess cover crop and conservation tillage adoption rates and potential adoption rates for quantifying GHG mitigation benefits. This approach is different than a recent analysis by LaRose and Myers (2019) where pastured cropland, hay land and haylage acres were removed from the total cropland acreage for cover crop and conservation tillage adoption rates. For the purposes of estimating GHG mitigation potential for managed croplands, we felt it was important to include the hayland acres because they have the potential to be used in rotation with current and future opportunities to be managed using cover cropping and conservation tillage practices.

A section defining critical limitations to using this data set for quantification of GHG mitigation opportunities is under development by the authors and will be provided as an amendment to the Appendix in the near future.

[1] CRP: Conservation Reserve Program; WRP: Wetlands Reserve Program; FWP: Farmable Wetlands Program; CREP: Conservation Reserve Enhancement Program

2.2.1 Current percent cover crop adoption (Eq 1)

Percent cover crop adoption was calculated as:

$$\frac{acres\ of\ cropland\ in\ a\ cover\ crop}{total\ cropland\ acres} \times 100\%$$

2.2.2 Percent no-till, reduced till, and intensive till adoption (Eq 2)

Percent no-till, reduced till, and intensive till levels were calculated as:

$$\frac{acres\ of\ no-till, reduced, or\ intensive\ till\ cropland}{sum\ of\ notill + reduced\ till + intensive\ till\ acres} \times 100\%$$

It should be noted that these three categories of reported tilled lands in the AgCensus do not typically sum to the total cropland acres for a given county. It is unclear what the tillage status of the unreported lands may be for the 2017 AgCensus data and thus, these lands were omitted from the calculation. This is similar to the approach by LaRose and Myers (2019) to summarize current U.S. no-till and conservation tillage adoption.

2.3 Estimating GHG reduction potential on cropland using cover cropping & conservation tillage

For cover crop practices, the COMET-Planner tool has a different ERC depending on irrigation status and whether a legume or non-legume species was planted. The tool does not account for mixed species cover crops. For many other practices, the ERC is different for irrigated and non-irrigated croplands. The appropriate ERC was multiplied by the estimated irrigated or non-irrigated acres to produce total CO_2e reduction values for each county and practice (tonnes CO_2e yr^{-1}). COMET-Planner provides ERCs for lands that were converted from (i) intensive tillage to no-till/strip till; (ii) reduced till to no-till/strip till; and (ii) intensive tillage to reduced till.

2.3.1 GHG reduction potential based on current cover crop adoption (Eq 3)

$$acres\ of\ cropland\ in\ cover\ crop\ \times Cover\ Crop\ Emission\ Reduction\ Coefficient$$

2.3.2 GHG reduction potential based on current no-till & reduced till adoption (Eq 4)

$$acres\ of\ cropland\ in\ reduced\ or\ no-tillage\ \times Emission\ Reduction\ Coefficient$$

2.3.3 GHG reduction potential based on remaining cropland adopting cover crops (Eq 5)

$$acres\ of\ cropland\ NOT\ in\ cover\ crop\ \times Cover\ Crop\ Emission\ Reduction\ Coefficient$$

2.3.4 GHG reduction potential based on remaining intensive tillage acres adopting no-till (Eq 6)

$$(acres\ of\ cropland\ in\ intensive\ tillage\ \times No-Till\ Emission\ Reduction\ Coefficient)$$

2.3.5 GHG reduction potential based on remaining intensive tillage acres adopting reduced till (Eq 7)

$$(acres\ of\ cropland\ in\ intensive\ tillage\ \times Reduced\ Till\ Emission\ Reduction\ Coefficient)$$

2.3.6 GHG reduction potential based on remaining reduced tillage acres adopting no-till (Eq 8)

$$(acres\ of\ cropland\ in\ reduced\ tillage\ \times No-Till\ Emission\ Reduction\ Coefficient)$$

Defining Irrigated Cropland Acreage using the 2017 Census of Agriculture

The CaRPE tool is scaled at the county level because the emission reduction coefficients in COMET-Planner are at the county level (primarily to account for differences in soils and climate); thus, state totals are calculated by summing the counties. The AgCensus will replace reported data with '(D)' in order to protect privacy when there are few farms reporting. This is the case for 6 counties in Maine. The sum of the reported counties is 16,771 irrigated harvested cropland acres (data not shown). The sum of the ag land irrigated acreage is 19,972 in the Ag Census. Since it is unclear from the AgCensus if all irrigated agland acres is appropriated to cropland, we take the proportion of cropland to grazing land and assign a weighted value, resulting in 19,881 acres (Table 1).

2.4 *Units for Greenhous Gas Emissions*

Greenhouse gas emissions are expressed as carbon dioxide equivalents (CO_2e) and reported in metric ton (tonnes) increments. Carbon dioxide equivalents are a global warming potential weighting that is based on radiative forcing over a 100-year time scale and resulting from the release of 1 kg of a substance as compared to 1 kg of CO_2 (IPCC, 2006, V4 Ch11). In COMET-Planner, the three main GHGs reported for each conservation practice are CO_2, N_2O, and CH_4. Carbon dioxide has a global warming potential of 1 and is used as the reference. Nitrous oxide has a global warming potential of 298 and CH_4 a global warming potential of 25 using a 100-year timescale (EPA, 2019). GHG reduction potential values are adjusted for the estimated irrigated and non-irrigated acres within each county.

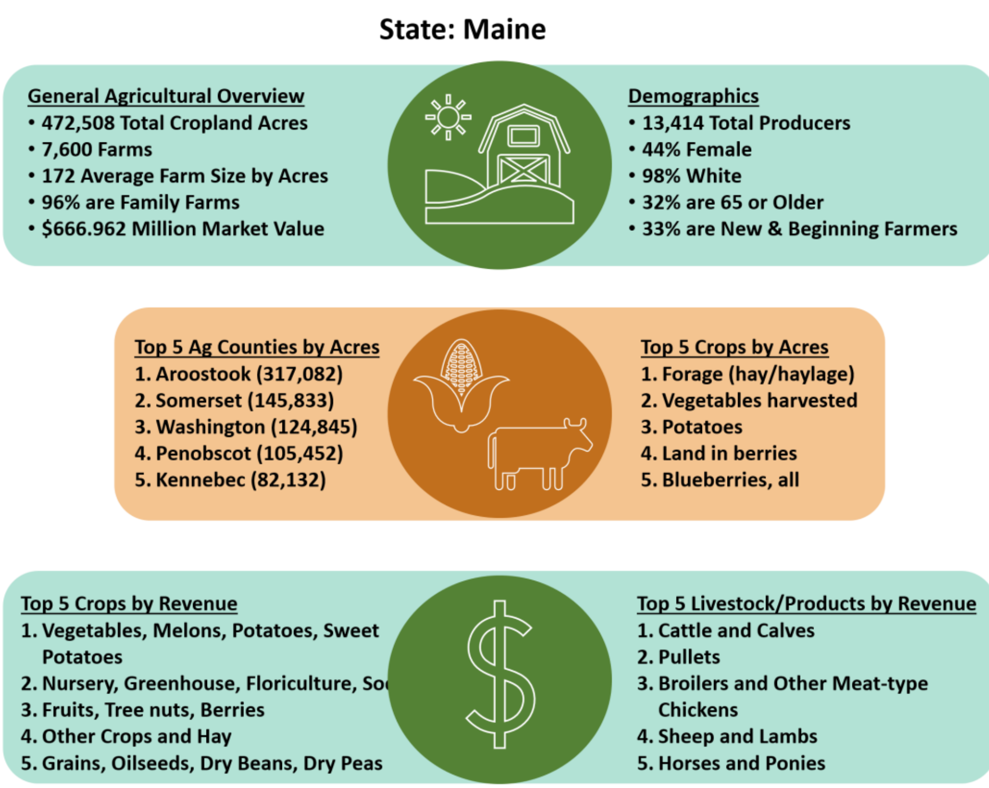
3 Results

3.1 Current State of Agriculture in Maine

The total amount of farmland in Maine is 1,307,613 acres with 472,508 of those acres under cropland (*Figure 2*). In 2017, there were 7,600 farms with a state average farm size of 172 acres (*Figure 2*). There are 313 farms that are greater than 500 acres in size. The dominant crops, by acreage, are forage (hay/haylage), vegetables, potatoes, berries, and blueberries. Cattle, pullets, broiler chickens, sheep, and horses are the predominant livestock or livestock products (*Figure 2)*. Total revenue from agricultural products is approximately $667 million with 61% of those revenues from crops and 39% from livestock, poultry and associated products (USDA-NASS, 2017c).

Demographically, the proportion of white producers in Maine (97.6%) is higher than the national average of 94.1%[2]. The proportion of female to male producers in Maine (43.7%) is higher than the national average of 36.1% (*Figure 2*; USDA-NASS, 2017c). In Maine, 31.9% of producers are 65 years and older. The national average age of producers is 57.5 with 33.9% over the age of 65.

Figure 2. Maine Agriculture at a Glance. Adapted from USDA-NASS (2017c).



[2] From 2017 Census Volume 1, Chapter 1: U.S. National Level Data. Table 52. Available online at https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/

3.2 Current Adoption of Cover Cropping & Conservation Tillage

In Maine, cropland accounts for 472,508 acres and pastureland comprises 62,369 acres (Table 1). Among the 11 northeastern states, Maine ranks fifth in total cropland acreage (Figure 3). In Maine, cover cropping is practiced on 55,462 acres or 11.7% of cropland, which is greater than the national average of 3.9 but slightly lower than the regional average of 12.7% (Figure 4). Based on the acreage of reported tillage in the 2017 AgCensus, approximately 14% of cropland is managed under no-tillage and 21% under reduced tillage (see 2.2.2 equation 2). Several recent reports use only reported tilled acreage in reporting adoption rates from AgCensus data instead of total cropland acreage since the tillage for those lands is unknown. However, Maine has a high amount of acreage with unreported tillage practices relative to the total cropland acreage leading the authors to report the no- and reduced tillage rates using total county cropland acreage. Conservation tillage adoption for Maine is lower than the regional no-till and reduced-till adoption levels of 49.3% and 26.5%, respectively (Figure 5). Nationally, adoption of no-till and reduced till are 37.0 and 34.6%[3], respectively.

Table 1. Maine agricultural land use and current adoption (2017) of conservation practices.

Agricultural Lands and Practices[1]	Value (acres or %)
Total cropland acres (reported)	472,508
Irrigated cropland acres (estimated)	19,881
Non-irrigated cropland acres (estimated)	452,627
Cover Cropping	
Cropland acres with cover crops (reported)	55,462
% cover crop (reported/total cropland)	11.7
Tillage	
No till cropland acres (reported)	21,676
Reduced till cropland acres (reported)	31,953
Intensive till cropland acres (reported)	99,167
Unknown till cropland acres (Total cropland minus sum of reported till)	319,712
% no-till (no-till/sum of reported till)	14.2
% reduced till (conservation till/sum of reported till)	20.9
Total pastureland (reported)	62,369
Irrigated pastureland (estimated)	91
Non-irrigated pastureland (estimated)	62,278

[1]See *Appendix* at end of document for selected conservation practice definitions.

[3] From 2017 Census Volume 1, Chapter 1: U.S. National Level Data. Table 47. Available online at https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/

Figure 3. Total cropland acres for the 11 Northeastern states. Total cropland acres for the region is 12.7 million acres.

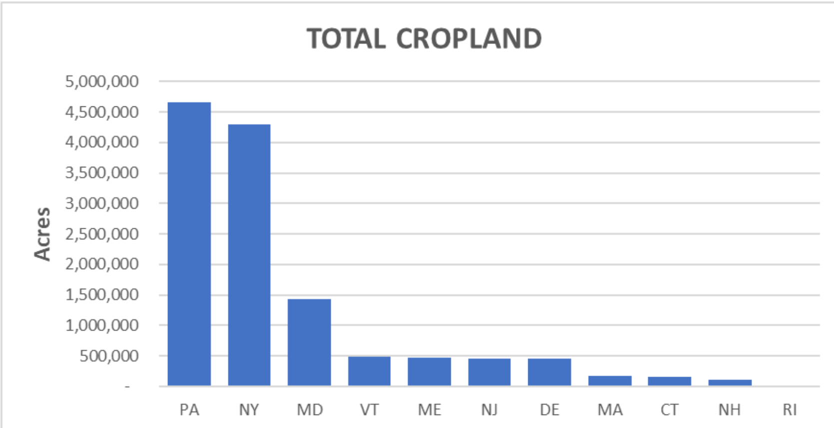


Figure 4. Percent cover crop adoption among the 11 Northeastern states (regional average is 12.7%).

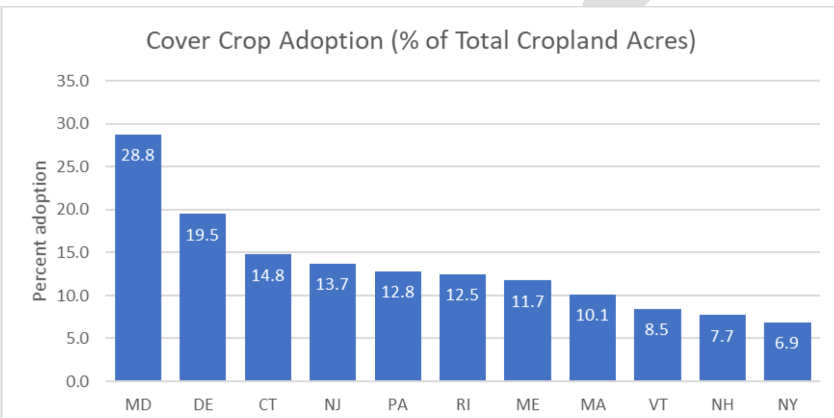
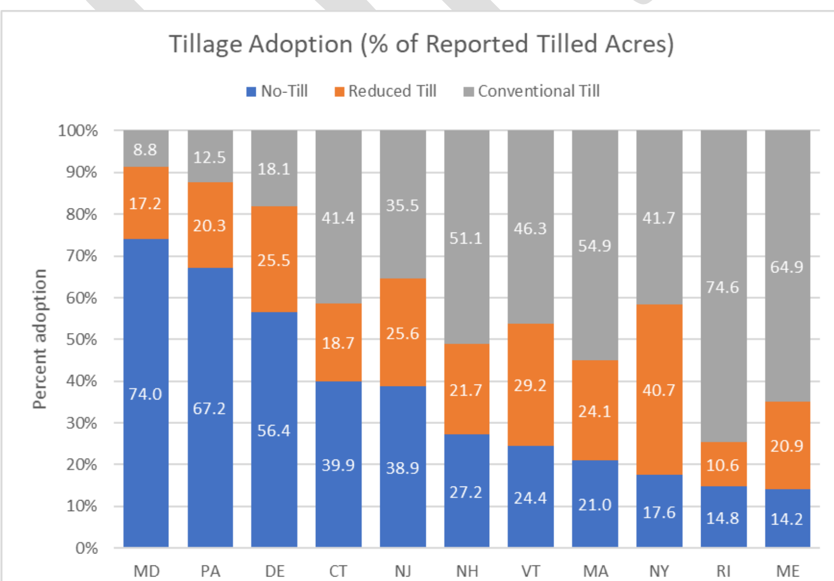


Figure 5. Percent no-till, reduced-till, and intensive till among the 11 Northeastern states sorted in order of greatest to lowest no-till adoption (regional average is 49.3% for no-till and 26.5% for reduced till).



3.2.1 Spatial Distribution of Cover Crop and Conservation Tillage Adoption

Cover crop adoption varied considerably among counties across the state ranging from 0 to 22.5% adoption (Figure 6). The five counties with the highest cover crop adoption rates ranged from 6.5 to 22.5% adoption (data not shown). Higher adoption rates tended to be located in the north to northeastern portion of the state (Figure 6). When sorting the data by % adoption (Figure 6a) as compared to total acreage (Figure 6b) under a conservation practice produced different results and highlights the importance of considering both when scaling and targeting GHG mitigation opportunities. On an acre basis, the five counties with the highest acreage of cover crops had a combined 49,557 acres with cover crops (Table 3).

Figure 6. Current (2017) cover crop adoption by percent (a) and acreage (b) across Maine.

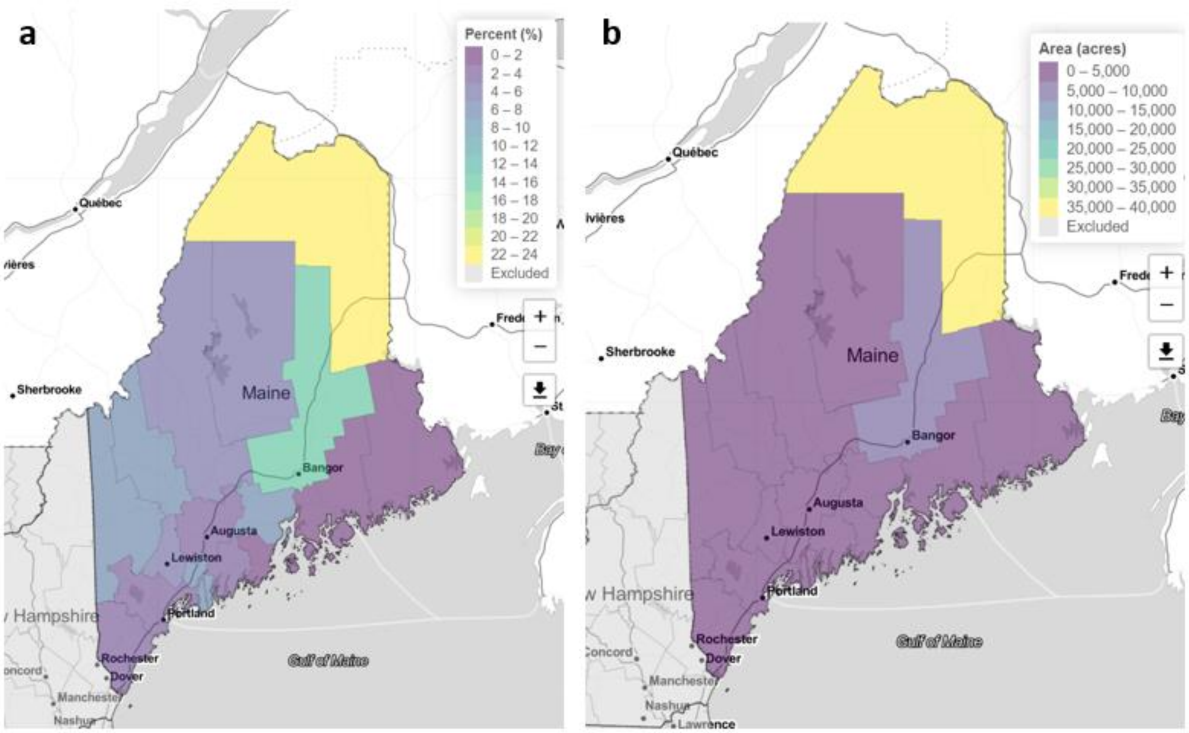


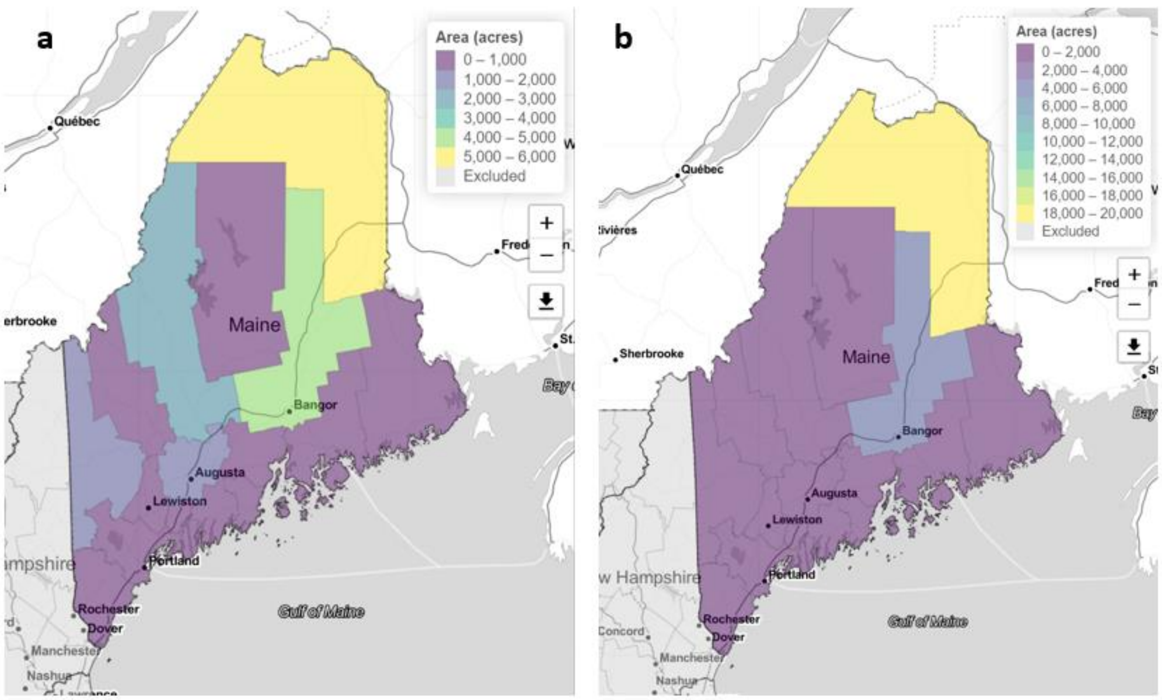
Table 2. Top five counties by acres of cover crops, no-tillage, and reduced-tillage practices (2017)[4].

County	Acres	% of Total
	Cover Crop	
Aroostook	39,096	22.5
Penobscot	5,978	14.5
Somerset	1,700	4.7
Androscoggin	1,423	5.8
Kennebec	1,360	3.7
	No-Till	
Aroostook	5,800	5.9
Penobscot	4,134	29.2
Somerset	2,705	38.2
Oxford	1,920	35.5
Kennebec	1,678	23.1
	Reduced-Till	
Aroostook	19,807	20.1
Penobscot	5,122	36.2
Kennebec	1,988	27.3
Androscoggin	1,534	32.3
Somerset	1,040	14.7

[4] Note: Table 2 represents the top 5 counties when sorted by the acres of conservation practice reported in 2017 AgCensus, rather than % adoption calculated from 2017 AgCensus data.

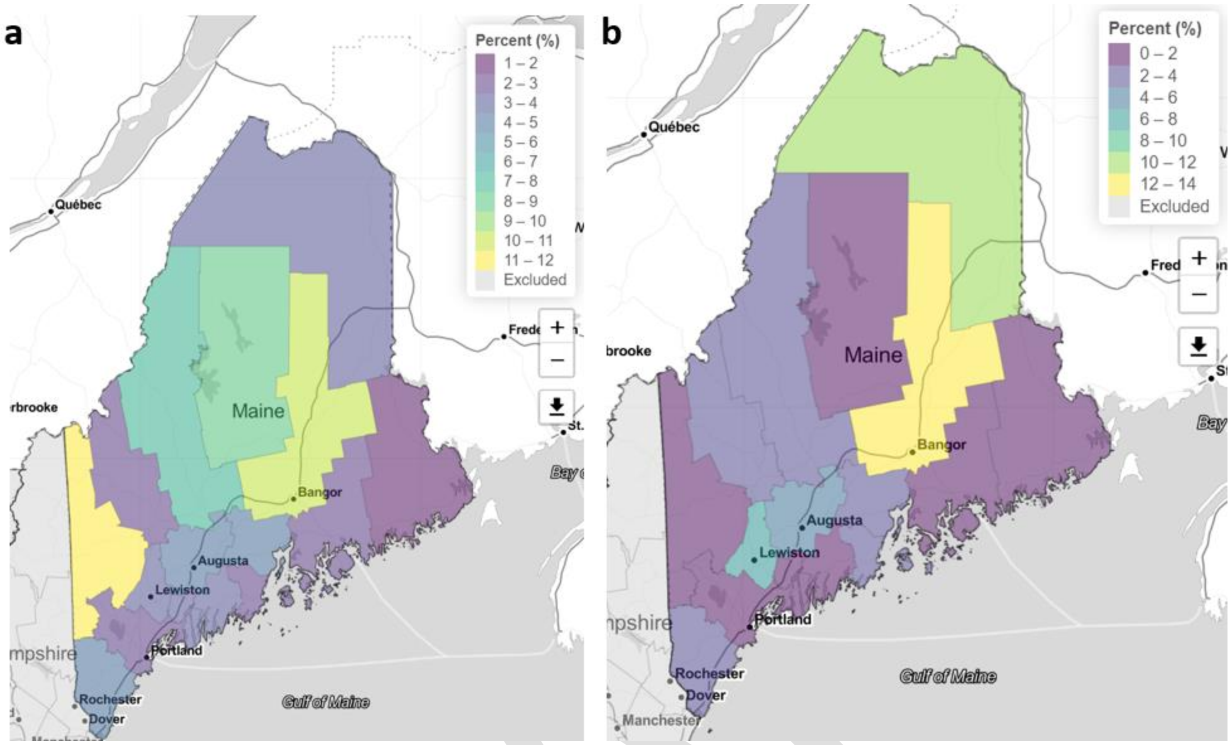
In 2017, Maine had almost 22 thousand and 32 thousand acres under no-till and reduced till, respectively (Table 1). Similar to cover crop adoption, adoption of no-till and reduced till varied at the county level (Figure 7*)*. The greatest acreage of no-tillage and reduced tillage were observed in northern Maine (Aroostook and Penobscot Counties). When Maine counties are sorted by acreage under no-tillage, the practice was observed to be concentrated in the northeastern portion of the state (Figure 7a) with the top five counties totaling 16,237 acres (Table 3).

Figure 7. Acreage under no-till (a) and reduced-till adoption (b) in 2017 across Maine.



The top five counties for no-till adoption based on acreage had associated adoption rates ranging from 5.9 to 38.2% (Table 2). Using the total cropland acreage, no-tillage adoption ranged from 1 to 12% and reduced tillage adoption ranged from 0 to 14% (Figure 8). The greatest no-tillage acreage was observed in Aroostook followed by Penobscot County. For no-tillage, hotspots of adoption were different when based on acreage (Figure 7a) as compared to percent adoption (Figure 8a). Reduced tillage adoption was predominant in Aroostook and Penobscot counties when sorted by both acres of adoption and percent adoption (Figure 7b and 8b).

Figure 8. Percent adoption of no-till (a) and reduced tillage (b) across Maine based on total cropland acres for each county[5].



3.3 Current & Future Potential GHG Benefits with Cover Crop and Conservation Tillage

The benefits from integrating cover crops have included but are not limited to reduction of runoff and soil erosion, improved nutrient retention, reduced weed pressure, and increased soil organic matter content (Hartwig and Ammon, 2002). Increasing soil organic C content from implementing cover cropping therefore has the potential to mitigate GHG emissions by sequestering C in the soil. Swan et al. (2019) estimate the C sequestration rate from cover cropping to range from 0.08 to 0.46 tonnes CO_2e ac^{-1} yr^{-1} and N_2O emission reductions of 0 to 0.10 tonnes CO_2e ac^{-1} yr^{-1} depending on climatic zone. Swan et al. (2019) estimate the C sequestration rate from converting from intensive tillage to reduced or no-tillage to range from 0.10 to 0.13 and 0.22 to 0.42 tonnes CO_2e ac^{-1} yr^{-1}, respectively. The lower C sequestration value represented dry/semiarid climate zones and the upper value moist/humid climatic zones. The N_2O emission reductions for converting from intensive to reduced tillage were 0.07 tonnes CO_2e ac^{-1} yr^{-1} regardless of climate zone. The N_2O emission reductions for converting from intensive to no-tillage ranged from -0.11 to 0.13 tonnes CO_2e ac^{-1} yr^{-1} for moist/humid and dry/semiarid, respectively (Swan et al., 2019).

From a GHG reduction perspective, current adoption of cover crops and conservation tillage in Maine has resulted in a potential reduction of 20,223 to 27,589 tonnes CO_2 e yr^{-1} depending if the cover crop was a non-legume or legume cover crop mix, respectively (Table 3). If all of the remaining cropland implemented a legume cover crop and the land currently in conventional till or reduced till went to no-till, the state could reduce GHG emissions by as much as 153,000 additional tonnes CO_2e for a total (current and remaining) potential of up to 181,000 tonnes CO_2e per year (Table 3). The majority of these benefits is realized through increased carbon sequestration in the soil with a portion associated with changes in N_2O emissions. The lower (102, 470 tonnes CO_2e yr^{-1}) and upper (181,000 tonnes CO_2e yr^{-1}) potential climate benefit from cover cropping and conservation tillage is equivalent to the amount of carbon that is sequestered by planting nearly 1.7 and 3 million tree seedlings that are grown for 10 years, respectively.

[5] Several recent reports use only reported tilled acreage in denominator instead of total cropland acreage since the tillage for those lands is unknown. However, Maine has a high amount of acreage with unreported tillage practices leading the authors to report the no- and reduced tillage rates using total county cropland acreage. See section 2.2.2

Table 3. Estimate of greenhouse gas reduction potential (metric tonnes CO_2 equivalents per year) with current adoption levels of cover cropping and conservation tillage practices (i.e. reduced and no-till). Calculated based on adoption of these practices on 100% of remaining cropland.[6]

Practice Category	Current or Remaining	Convert from	Converted to	Tonnes $CO_2e\ yr^{-1}$	Equiv to C seq by ## tree seedlings grown for 10 y
			Lower Potential[1]		
Cover Crop	Current	No cover	non-legume	6,912	114,291
	Remaining[3]	No cover	non-legume	53,600	886,270
Tillage	Current	Intensive till	Reduced till	5,392	89,162
	Current	Reduced till	No-till	7,919	130,933
	Remaining[3]	Intensive till	Reduced till	16,817	278,067
	Remaining[3]	Reduced till	No-till	11,830	195,617
Potential	Current			20,223	334,386
Mitigation	Remaining			82,247	1,359,955
Sum	**Total**			**102,470**	**1,694,341**
			Upper Potential[2]		
Cover Crop	Current	No cover	Legume	12,054	199,312
	Remaining[4]	No cover	Legume	94,020	1,554,620
Tillage	Current	Intensive till	Reduced till	5,392	89,162
	Current	Intensive till	No-till	10,143	167,716
	Remaining[4]	Intensive till	No-till	47,188	780,261
	Remaining[4]	Reduced till	No-till	11,830	195,617
Potential	Current			27,589	456,190
Mitigation	Remaining			153,039	2,530,498
Sum	**Total**			**180,628**	**2,986,688**

[1]Current estimates are based off of 2017 Ag Census acres of adoption of cover crop, no-till or reduced till data coupled with COMET-planner GHG emission coefficients at the county level and summed for the state. Lower potential example shown assumes a non-legume cover crop and tillage conversion from intentive and reduced tillage scenarios.

[2]Current estimates are based off of 2017 Ag Census acres of adoption of cover crop, no-till or reduced till data coupled with COMET-planner GHG emission coefficients at the county level and summed for the state. Upper potential example shown assumes a legume cover crop and greatest potential from tillage conversion to no-tillage.

[3]Remaining estimates are based off the cropland not in cover crop adopting non-legume cover crop and for cropland currently in intensive till to convert to reduced tillage and for cropland currently in reduced till to convert

[4]Remaining estimates are based off the cropland not in cover crop adopting a legume cover crop and for cropland currently in intensive and reduced tillage to convert to no-till.

[6] Estimates in Table 3 do not reflect GHG mitigation or C sequestration in cropland acreage where the tillage status was unreported.

Maine had a uniquely high number of acres (319,712 ac) in the 2017 AgCensus in which tillage was not reported (Table 4). Since the tillage and cropping systems were unknown for these acres, we provided an estimate of the GHG benefit that could occur on these lands assuming these lands were non-irrigated. The COMET-Planner non-irrigated emission reduction coefficients, when applied to the acres of unknown tillage, could provide an additional 51,154 to 145,161 tonnes CO_2e per year if those lands are under intensive tillage and converted to reduced or no-tillage, respectively (Table 4).

Table 4. Additional potential GHG reduction, in tonnes CO_2e yr^{-1}, if all cropland with unreported acreage in 2017 AgCensus was under non-irrigated intensive tillage and converted to conservation tillage.

County	Tillage Not Reported	GHG Benefit If Converted from Intensive Tillage to	
		No Tillage	Reduced Tillage
	Acres	--------------------- Tonnes CO_2e yr^{-1}	---------------------
ANDROSCOGGIN	19,810	9,113	3,170
AROOSTOOK	75,569	34,006	12,091
CUMBERLAND	13,484	6,203	2,157
FRANKLIN	10,050	4,523	1,608
HANCOCK	13,978	6,430	2,236
KENNEBEC	29,266	13,462	4,683
KNOX	8,875	4,083	1,420
LINCOLN	5,462	2,513	874
OXFORD	12,050	5,423	1,928
PENOBSCOT	27,001	12,150	4,320
PISCATAQUIS	6,822	3,070	1,092
SAGADAHOC	4,782	2,200	765
SOMERSET	28,750	12,938	4,600
WALDO	18,508	8,514	2,961
WASHINGTON	30,412	13,685	4,866
YORK	14,893	6,851	2,383
Statewide Total	**319,712**	**145,161**	**51,154**

The greatest GHG emission offsets for cover cropping are likely to be realized in those counties with the largest acreage yet to adopt legume cover crops. The ten counties within the state that could provide the greatest GHG reductions if the remaining acres adopted legume cover crops are listed in Table 5. Overall, GHG emission reductions from increased adoption on these acres is estimated to be 81,200 tonnes CO_2e per year. Given a 20-year CO_2 reduction benefit from adopting this conservation practice (Swan et al., 2019), this would result in an overall climate benefit of approximately 1.62 million metric tonnes CO_2e.

Table 5. Top 10 Maine counties with the greatest potential CO_2e reduction if all cropland that did not have a cover crop adopted legume cover crops.

County	Amount of cropland without cover crops (acres)	Reduction if cover crops adopted on all remaining cropland (tonnes CO_2e yr^{-1})
Aroostook	134,947	28,827
Kennebec	35,177	8,792
Penobscot	35,169	7,455
Somerset	34,140	7,183
Washington	31,065	6,524
Androscoggin	23,140	5,775
Waldo	20,190	5,048
York	17,688	4,406
Oxford	16,304	3,461
Hancock	14,928	3,730

Similar to cover cropping, the greatest GHG emission offsets for conservation tillage (i.e., no-tillage or reduced tillage) are likely to be realized in those counties with the largest acreage of intensive tillage. Table 6 shows ten counties within the state that could provide the greatest GHG reductions if the remaining acres converted from intensive tillage to no-tillage. Overall, GHG emission reductions from increased adoption on these acres is estimated to be 45,924 tonnes CO_2e per year. Given a 20-year CO_2 reduction potential for conservation tillage adoption would result in a climate benefit of nearly 0.92 million tonnes CO_2e.

Table 6. Top 10 counties with the greatest potential CO_2e reduction if all land currently in intensive tillage adopted no-till practices[1].

County	Amount of cropland in intensive till (acres)	Remaining GHG potential reduction (MT CO_2e yr^{-1})
Aroostook	72,867	34,951
Penobscot	4,890	2,280
Kennebec	3,605	1,664
Oxford	3,373	1,580
Somerset	3,345	1,516
Androscoggin	2,340	1,104
York	2,210	1,071
Waldo	1,663	765
Cumberland	1,113	528
Piscataquis	1,024	463

[1]Estimates do not include land on which tillage practice is unknown.

3.4 Additional Cropping System GHG Reduction Potential Opportunities

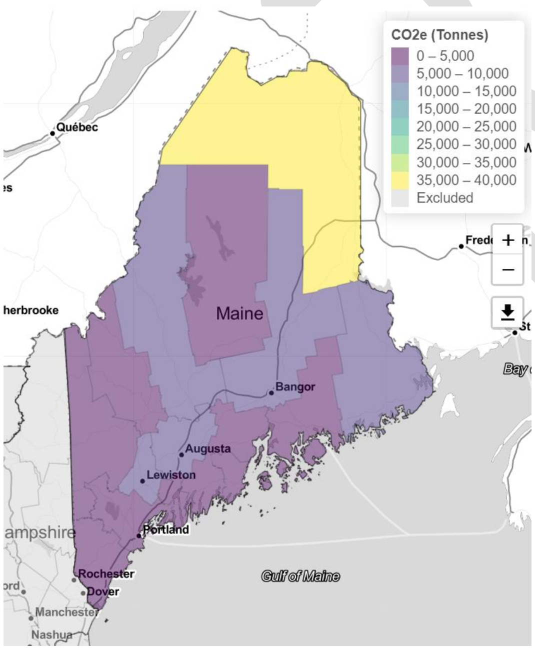
In addition to cover crops and conservation tillage, there are several other practices identified by USDA-NRCS to provide a co-benefit of GHG emission reductions in addition to conservation of natural resources (Table 7). For example, adopting improved nutrient management by replacing 20% of synthetic nitrogen with compost (25:1 carbon to nitrogen ratio) on all cropland could reduce GHG emissions by 213,572 tonnes CO_2e yr^{-1} and silvopasture 83,574 tonnes CO_2e yr^{-1}. Across all Maine cropland, adopting a conservation crop rotation could reduce GHG emissions by a little over 100,000 tonnes CO_2e yr^{-1}. However, GHG benefits from conservation crop rotation adoption varies within the state from 0 to 40,000 tonnes CO_2e yr^{-1} across counties (Figure 9).

Table 7. Greenhouse gas reduction (CO_2e) potential for Maine based on all cropland adopting example conservation practices identified from COMET-Planner (i.e., 100% adoption).

Conservation Practice	Conservation Practice Implementation	GHG Reduction (tonnes CO_2e yr^{-1})
Residue and Tillage	Intensive till to no-till/strip till	221,732
Nutrient Management	Replace syn N w/compost25[1]	213,572
Cover Crop	Legume Cover Crop	106,074
Mulching	Mulching	151,203
Stripcropping	Stripcropping	113,402
Conservation Crop Rotation	Conservation Crop Rotation	103,952
Silvopasture	Silvopasture	83,574
Range Planting	Range planting	31,185
Combustion System Improvement	Fuel	4,725
Prescribed Grazing	Prescribed grazing	1,248

[1] syn = synthetic nitrogen fertilizer and compost25 refers to application of a compost with a 25:1 C:N ratio.

Figure 9. Greenhouse gas reduction potential (MT CO_2e yr^{-1}) for Maine under scenario where all cropland implements conservation crop rotation.



Recognizing that 100% adoption of any one practice at state-level is not likely, we present one scenario whereby we combined the current levels of adoption of cover cropping and conservation tillage and then project the additional greenhouse gas reduction benefits by adopting cover cropping on 25% of the remaining cropland, reduced or no-till on 75% of lands currently in intensive tillage, and adoption of nutrient management that replaces 25 % of synthetic nitrogen on 25% of croplands with either dairy manure or compost with 25:1 carbon to nitrogen ratio (Table 8). Under this scenario (i.e., cover cropping, tillage management, and nutrient management), Maine could reduce GHG emissions by approximately 66 to 143 thousand tonnes CO_2e per year. Given a 20-year CO_2 reduction benefit from adopting conservation practices (Swan et al., 2019), this would result in an overall climate benefit of 1.33 to 2.87 million metric tonnes CO_2e for this scenario. This equates to the amount of C sequestered by approximately 1.1 to 2.4 million tree seedlings grown for 10 years using the EPA GHG equivalency calculator (https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator).

Table 8. One scenario for greenhouse gas reductions for Maine by coupling cover cropping and tillage and nutrient management on cropland.

Practice Category	Convert from baseline to	Tonnes $CO_2e\ yr^{-1}$	Equiv. to C seq by ## tree seedlings grown for 10 y
Cover Crop[1]	Non-Legume	20,312	335,859
	Legume	35,559	587,967
Tillage[2]	Reduced till	26,878	444,426
	No-till	54,407	899,625
Nutrient Management[3]	Dairy manure	19,260	318,460
	25:1 compost	53,393	882,852
Potential Mitigation Sum	Lower	66,450	1,098,745
	Upper	143,359	2,370,443

[1] Current cover crop adoption plus 25% adoption on remaining lands not in cover crops.
[2] Current no-tillage adoption plus 75% adoption on remaining intensive tillage lands.
[3] Replacing synthetic fertilizer with dairy manure or 25:1 compost on 25% of cropland acres.

4 Future/Ongoing Work

- State specific case studies with proper stacking of practices.
- A section on limitations and uncertainties of the data.
- A section on feasibility/considerations states should consider for practice adoption. Recommend states work with AFT as well as local experts/knowledge to develop opportunities that may be more practical/feasible for state specific ag conditions.
- A section on costs of practices for the state based on NRCS Practice Estimates.
- Appendix of calculations – Available on request

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6 Appendix

6.1 Glossary

The following conservation practices are as defined in companion report to www.comet-planner.com by Swan et al. and follow the NRCS Conservation Practice Standard (CPS) Definitions; please see cited reference for more details on COMET-Planner Practice Implementation Information:

Combustion System Improvement (CPS 372) - Improved Farm Equipment Fuel Efficiency. Installing, replacing, or retrofitting agricultural combustion systems and/or related components or devices for air quality and energy efficiency improvement.

Conservation Crop Rotation (CPS 328) - Decrease fallow frequency or add perennial crops to rotations. A planned sequence of crops grown on the same ground over a period of time (i.e. the rotation cycle).

Cover Crops (CPS 340) - Cover crops are grasses, legumes, and forbes planted for seasonal vegetative cover. COMET-Planner explores two options where either a legume or non-legume seasonal cover crop is added to irrigated or non-irrigated cropland.

Mulching (CPS 484) - Add Mulch to Croplands. Applying plant residues or other suitable materials produced off site, to the land surface.

Nutrient Management (CPS 590) –Managing the amount (rate), source, placement (method of application), and timing of plant nutrients and soil amendments. Two example practices are included here but many exist in COMET-Planner.

- **Replace Synthetic N Fertilizer with Dairy Manure** on Irrigated/Non-Irrigated Croplands. COMET-Planner specific info: The management scenario assumes that synthetic nitrogen fertilizer amounts are gradually reduced by approximately 4% per year for 5 years, achieving a 20% reduction in nitrogen fertilizer use after the 5th year and remaining constant at that level in the years that follow. Manure is added at a rate that supplies 20% of the total nitrogen applied to the system.
- **Replace Synthetic N Fertilizer with Compost (C:N ratio of 25)** on Irrigated/Non-Irrigated Croplands. The management scenario assumes that synthetic nitrogen fertilizer amounts are

gradually reduced by approximately 4% per year for 5 years, achieving a 20% reduction in nitrogen fertilizer use after the 5th year and remaining constant at that level in the years that follow. Compost is added at a rate that supplies 20% of the total nitrogen applied to the system.

Residue and Tillage Management - No-Till (CPS 329) - **Intensive Till to No-Till or Strip-Till** on Irrigated/Non-Irrigated Cropland. Limiting soil disturbance to manage the amount, orientation and distribution of crop and plant residue on the soil surface year around.

Residue and Tillage Management - No-Till (CPS 329) - **Reduced Till to No Till or Strip Till** on Irrigated/Non-Irrigated Cropland. Limiting soil disturbance to manage the amount, orientation and distribution of crop and plant residue on the soil surface year around.

Residue and Tillage Management – Reduced Till (CPS 345) - Intensive Till to Reduced Till on Irrigated/Non-Irrigated Cropland. Managing the amount, orientation and distribution of crop and other plant residue on the soil surface year-round while limiting the soil-disturbing activities used to grow and harvest crops in systems where the field surface is tilled prior to planting.

Stripcropping (CPS 585) - Add Perennial Cover Grown in Strips with Irrigated/Non-Irrigated Annual Crops. Growing planned rotations of row crops, forages, small grains, or fallow in a systematic arrangement of equal width strips across a field.

6.2 Critical Data Set Limitations

A section defining critical limitations to using this data set for a science-based estimate of GHG mitigation opportunities is under development by the authors and will be provided as an amendment to the Appendix soon.

6.3 Additional Calculations

6.3.1 Description of calculations for estimating the range of GHG reduction potential based on current adoption levels and adoption on remaining cropland.

Adoption Status	GHG Reduction Estimate Calculation	
	Lower Range	**Upper range**
Current		
Current acres in cover cropping	assumes lands converted FROM no cover TO a non-legume cover	assumes lands converted FROM no cover TO a legume cover
Current acres in no-till	lands converted FROM reduced till status	lands converted FROM intensive till status
Current acres in reduced till	lands converted FROM intensive till status	lands converted FROM intensive till status
Remaining		
Acres currently not in cover crop	lands convert TO a non-legume cover	lands convert TO a legume cover
Acres currently in intensive till	lands convert TO reduced till	lands convert TO no-till
Acres currently in reduced till	lands convert TO no-till	lands convert TO no-till
Acres currently in unknown till status	lands convert TO reduced till	lands convert TO no-till